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DAYLIGHTING DESIGN OVERLAYS
FOR EQUIDISTANT SUN-PATH PROJECTIONS

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ABSTRACT

Projections of the sun's daily and seasonal paths frequently are used to solve building design problems involving site obstructions and shading of fenestration. In the United States, equidistant projections are perhaps the most widely used (compared to other sun-path projections) because of the commercial availability of a complete set of sun-path diagrams for a range of useful latitudes.

This paper describes the development of a set of overlays designed for use with sun-path projections to predict illumination on any building surface throughout the year for standard climatological conditions. Illumination is calculated for clear and overcast skies and for direct sunlight using algorithms recommended by the CIE. Values for illumination incident upon the surface, as well as transmitted through single and double glazing, can be calculated. Similar overlays for solar radiation are being developed.

With these overlays, a sun-path diagram becomes a more versatile and powerful design tool for solving a wide range of siting, sun control, thermal transfer, and daylighting problems.

1. INTRODUCTION

Adequate data on the availability of daylight is a prerequisite for effectively utilizing daylighting strategies in commercial buildings. The data required and their optimal format vary considerably, as do other climatic data required for building design. Requirements for daylighting data can be divided into three categories based upon final purpose.

1.1 Hourly Data for Annual Energy Analysis

Hourly data for a typical year (i.e., a data set whose average properties and ranges are typical of the long-term average for the site) can be determined from direct measurements or by conversion from solar radiation data. Long-term empirical data are virtually nonexistent in the United States, although data are now being collected at several locations. Short-term illumination data collected simultaneously with insolation data are used to determine coefficients for the

luminous efficacy of skylight and sunlight. These coefficients can then be used to convert solar radiation data to daylighting data. When designed for use with large computer models, the data generally would be provided on magnetic tape. Appropriate hourly, monthly, or seasonal values could also be calculated and displayed in tabular or graphic form.

1.2 Frequency Distribution of Daylighting Resource Data

A building designer may know that when the exterior illuminance on a horizontal or vertical surface exceeds a critical value, the electric lights will be turned off. It would also be useful to know the fraction of the year (or season) that the critical value of exterior illuminance is exceeded. Other exterior illuminance values could be correlated with dimming levels of electric lighting. Another useful tool would be a histogram showing the frequency of occurrence of each illuminance value, and the cumulative probability of any particular value being equaled or exceeded. These data can be measured or calculated, and once determined can be presented in a variety of tabular or graphic formats.

1.3 Design Illuminance Data

The data most frequently required by an architect or engineer are likely to be answers to questions such as, "What is the hourly illuminance on a vertical surface facing northwest on a typical clear (cloudy) day in June (December) at a specific building site?" or "What is the optimum orientation of a window for providing maximum daylight exposure?" The data required to answer these questions are nominal clear or overcast daylight illuminance values, which for a given site (latitude) and for assumed atmospheric conditions (turbidity, humidity) are a function only of window orientation and solar position. Again, this type of data could be displayed in tabular or graphic form.

Research efforts to provide all three types of daylighting data are in progress as part of a Daylighting Resource Assessment project at LBL. This paper describes one effort to develop design illuminance data in a format that a building designer can use easily.

2. BACKGROUND

The primary source for design illuminance data in the United States are the clear and overcast day values given in the IES Handbook¹ and in the Recommended Practice of Daylighting.² These data are derived from measurements made in Washington, DC., in the 1920's. These nominal values have probably shifted over time, and it is questionable how representative they are for locations as diverse as Phoenix and Seattle. Nonetheless, since no other data are available these values will continue to be used. Because the data are given as a function of solar altitude, determining hourly values is a tedious task. Comparing hourly illuminance values for two or more surfaces requires additional calculations. The data could be provided in tabular form, but one would want hourly data for each latitude and for each month or season, requiring lengthy tables such as the tables of Solar Heat Gain Factors in the ASHRAE Handbook of Fundamentals.³

We first discuss the selection of a different format for presenting design illuminance data. In a later section we discuss the source of that illuminance data. A projection of the sky vault onto a flat plane is a more compact tool for presenting such data. On such a projection, the sun's position for any hour, day, season, and latitude is a point, and the sun's apparent arc across the sky during one day is converted to a continuous line on the projection. Three different projections are commonly used: stereographic, equidistant, and orthographic. Lines of equal solar altitude appear as concentric circles in all three projections, but the spacing between the circles differs. The stereographic projection expands the spacing between circles of low solar altitude; the orthographic contracts the spacing between circles of low solar altitude; and the equidistant provides equal spacing between all circles. Each projection has properties that make it useful for other purposes as well. We confine our attention to the equidistant projection because of the commercial availability of a complete set of sun-angle diagrams for latitudes of interest in the United States.

Sun-path projections allow one to determine the effects of site obstructions, profile angles, incidence angles, shading masks, and other factors. The purpose of this study was to present the illuminance data described previously as an overlay that would be compatible with the equidistant sun-path projection. This extends the usefulness of the sun-path projection by allowing rapid determination of daylight illuminance (from skylight and sunlight) at a building surface or as transmitted through glazing. Similar procedures can be used to determine values

for solar radiation incident upon surfaces or transmitted through glazing. These will be discussed in a later paper.

It should be noted that using these overlays to determine daylight illuminance differs from using them to determine the position of the sun or the proper site for an overhang. For our use, when the overlay is oriented properly on the sky vault projection (to simulate window orientation), each point on the projection represents a possible position of the sun in the sky, characterized by an altitude and an azimuth angle. For a given orientation of a vertical window (azimuth angle), the illumination at the window from the sun and/or sky is uniquely defined by the wall-solar azimuth angle and the solar altitude. This allows a single overlay to be used to predict illumination for any vertical window. Even simpler overlays are possible for overcast skies, and for illumination on a horizontal surface. These are discussed in more detail in Section 3.2.

3. DEVELOPMENT OF THE OVERLAYS

Given a decision to use the equidistant projection, three tasks remained:

- 1) To select the algorithm for calculating daylight data.
- 2) To identify the specific daylight values to be plotted--e.g., clear-sky illuminance on a vertical surface.
- 3) To write a computer program to calculate the desired values and to produce contour plots for use as overlays.

3.1 Illuminance Model

The best documented and validated illuminance model for clear and overcast skies is that developed by the Commission Internationale de l'Eclairage (CIE).⁴ The CIE has developed formulae for sky luminance distribution for standard clear and overcast skies. These formulae relate the luminance at any point in the sky vault to the zenith luminance, the value of which can also be determined. Overcast sky luminance is a function of altitude only, with no azimuthal variation. Zenith luminance under overcast skies is a function of solar altitude. Clear-sky luminance distribution is a more complex function of altitude, azimuth, sun position, and two atmospheric parameters--turbidity and precipitable water vapor. Zenith luminance under clear skies is also a function of turbidity, water vapor, and solar altitude.

3.2 Overlays

The number of possible overlays increases quickly unless one limits the selection of data. In some cases a complete circular

overlay is required for a single parameter (e.g., clear-sky/vertical surface illuminance); in other cases half of a circular overlay is required (e.g., direct illumination/vertical surface); and in still others all that is necessary is a single line extending from the center to the edge of the projection (e.g., horizontal illuminance/overcast sky). The number of overlays could be doubled if incident and transmitted values are both desired. The following choices appear useful.

Clear sky:

1. Vertical surface/sky only (0)
2. Vertical surface/sky plus ground-reflected component (0)
3. Vertical surface/sun only (0)
4. Vertical surface/sky plus sun (0)
5. Vertical surface/sky plus sun plus ground-reflected component (0)
6. Horizontal surface/sky only (1)
7. Horizontal surface/sun only (1)
8. Horizontal surface/sky plus sun (1)
9. Sloped glazing/sky only; wall-solar azimuth: 0,90,180 (0)
10. Sloped glazing/sun only; wall-solar azimuth: 0,90,180 (0)
11. Sloped glazing/sun plus sky; wall-solar azimuth: 0,90,180 (0)

Notes:

(0) requires entire circular projection.

(0) requires one-half circular projection.

(1) requires a line from center to perimeter of projection.

For all clear-sky conditions, the values will change as values for turbidity and water vapor change. The CIE has defined nominal values for three turbidity conditions: rural, urban, industrial; and for three precipitable water-vapor conditions: arid, temperate, tropical. Thus one could generate a set of nine overlays for each of the above cases, or ninety-nine overlays; 198 could be generated if incident and transmitted values are desired.

Overcast Sky:

1. Vertical surface/sky only
2. Vertical surface/sky plus ground-reflected component
3. Horizontal surface/sky only
4. Sloped glazing/sky only

To reduce the number of overlays, we have chosen standard clear-day values of turbidity (urban) and water-vapor (temperate) for the first set of overlays. However, for the horizontal surface overlay, which requires only values plotted along a single radius, a three-segmented pie-chart was developed which displays results for the three discrete turbidity values and for a continuous range of precipitable water vapor. (See Fig. 3) Additional work is required to determine the most useful and practical set of overlays.

3.3 Computer Model

A computer model, SKY 1, was written to generate the overlays. SKY 1 is based upon the CIE clear sky, overcast sky, and sun models. For the sky conditions selected, the program calculates the illuminance incident at a given surface by integrating the contribution from the sky (and ground if desired) as received by the surface. This calculation is repeated for a large number of points on the sky-vault projection. The calculation at each point represents the sky (and/or ground; and/or sun) contribution for the unique set of conditions for the sun at that point in the sky vault. A contour plotting routine is then used to produce isolux contours on the circular projection. If transmitted illumination is desired, the program calculates transmission as a function of angle of incidence for light arriving from all sectors of the sky.

4. RESULTS

Computer-generated contour plots for three different cases are shown in Figs. 1, 2, and 3.

4.1 Clear Sky and Sun

Case 1: Vertical Surface Illuminance, Clear Sky (Fig. 1)

(Urban Atmosphere, Temperate Climate)

This contour plot provides incident illumination from a clear sky on a vertical surface. Atmospheric properties are explained in the figure caption. The overlay would be placed over the sun-path projection for the desired latitude, with the "Normal to Surface" arrow properly oriented relative to the sun-path diagram. To find the sky illumination for any hour, day, and month, first find the appropriate position on the sun-path diagram

and interpolate to find the illuminance value at that point on the overlay. For any surface of fixed orientation, incident illumination for any hour of any day of the year can be read directly from the overlay. Multiply numbers by 100 to obtain footcandles. A similar overlay, which accounts for glazing losses, has been generated for illumination transmitted through clear, double-strength, 1/8" single glazing.

Case 2: Vertical Surface Illuminance, Direct Sun (Fig. 2)

(A) Incident on Surface, (B) Transmitted

This figure combines two contour plots for direct illumination from the sun, one for incident illumination on the surface, the second for transmitted illumination. Move the overlay on the sun-path projection, with the arrow on the "Incident" half of the overlay properly oriented relative to the sun-path projection. As in Case 1 above, once the overlay is correctly positioned on the sun-path projection, the sun's illumination on the vertical surface at any hour of any day can be read immediately from the overlay. To determine the transmitted illumination, shift the overlay so that the arrow on the "Transmitted" portion is properly oriented. Note that the two contour plots are entirely independent; they are combined on the one overlay to reduce the number of overlays required.

Case 3: Horizontal Surface Illuminance, Clear Sky (Fig. 3)

(Variable Range of Turbidity and Humidity)

For a given atmospheric condition the overlay for clear-sky illumination on a horizontal surface depends only on solar altitude and so would simply be a line stretching from the center of the overlay to the perimeter, given an appropriate scale to indicate illuminance values. To provide more climate-sensitive information, the three sectors of the overlay include turbidity levels characteristic of rural, urban, and industrial atmospheres. For each turbidity sector, we then continuously vary the humidity (given as precipitable water vapor, cm) from 0 to 5, representing a range from arid to moist. To use the overlay, first identify the appropriate turbidity sector (e.g., urban) and the humidity level characteristic of the site and season. Then locate the desired hour and day on the sun-path projection. Now rotate the overlay until an imaginary line drawn from the center of the overlay to the perimeter at the appropriate humidity level intersects the hour/day point on the sun-path projection. Interpolate at this point of intersection to find the illumination value.

4.2 Overcast Sky

Overlays for overcast sky conditions depend only on solar altitude and are thus each a single line stretching from the center of the overlay to the perimeter. The best format for displaying these data on a single overlay is currently being studied.

Solar radiation overlays for the equidistant projections are also being developed. Several sets of overlays for solar radiation and illumination have been published previously, but most have been generated for stereographic projections. The algorithms on which the others are based are not well documented.

A complete set of the daylighting and solar radiation overlays discussed in this paper will be available at a later date.

5. ACKNOWLEDGEMENTS

The author gratefully acknowledges the assistance of Rick Creswick, who wrote the computer program, SKY, which calculates daylight illumination using CIE formulae and then generates the contour plots from which the overlays are derived.

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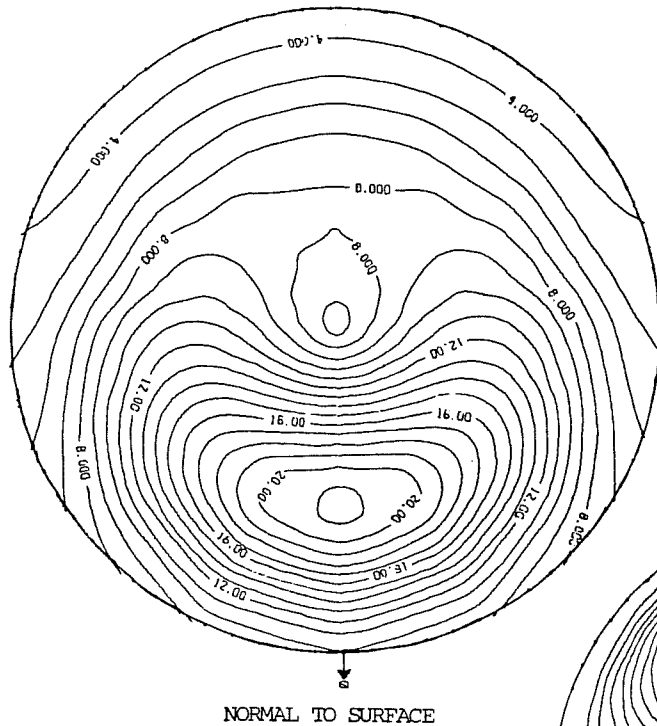


Fig. 2. Illuminance from direct sun-light incident on a vertical surface (A) and transmitted through single glazing with no absorptance (B). Turbidity based upon urban atmosphere ($\beta=.1$); temperate climate (precipitable water vapor, $w = 3\text{cm.}$). To obtain values in footcandles, multiply contour values by 100. Contour interval: 300 footcandles.

Fig. 1. Illuminance from clear sky inci-dent on a vertical surface. Turbidity factor based upon urban atmosphere ($\beta=.1$); temperate climate (precipitable water vapor, $w = 3\text{cm.}$). To obtain values in footcandles, multiply contour values by 100. Contour intervals: 100 footcandles.

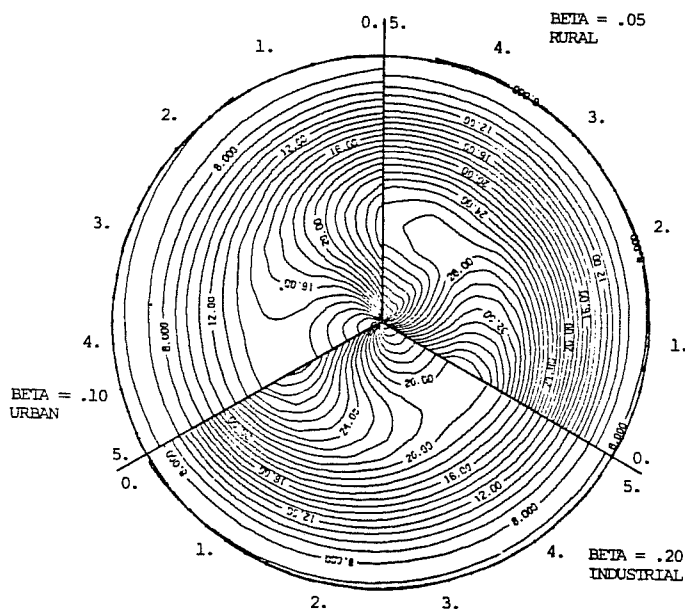
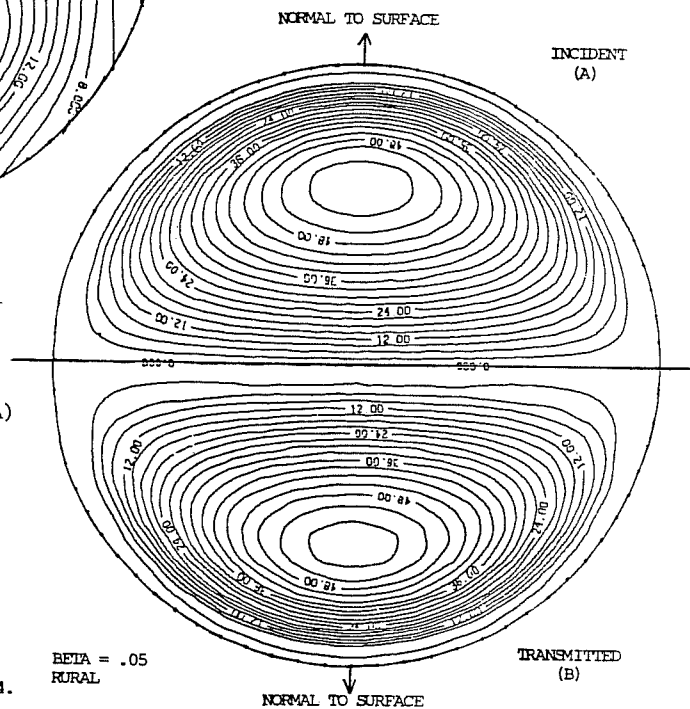


Fig. 3. Illuminance from clear sky on a horizontal surface for three turbidity values ($BETA$) and for a range of atmospheric water-vapor conditions (0-5 cm, shown along the outer edge with 0 = arid and 5 = humid).